Transmission of vibration through glove materials: effects of contact force

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Abstract

This study investigated effects of applied force on the apparent mass of the hand, the dynamic stiffness of glove materials, and the transmission of vibration to the hand. For 10 subjects, three glove materials, and three contact forces, apparent masses and glove transmissibilities were measured at the palm and at a finger at frequencies in the range 5 to 300 Hz. The dynamic stiffnesses of the materials were also measured. With increasing force, the dynamic stiffnesses of the materials increased, the apparent mass at the palm increased at frequencies greater than the resonance, and the apparent mass at the finger increased at low frequencies. The effects of force on transmissibilities therefore differed between materials and depended on vibration frequency, but changes in apparent mass and dynamic stiffness had predictable effects on material transmissibility. Depending on the glove material, the transmission of vibration through a glove can be increased or decreased when increasing the applied force.

Keywords: Anti-vibration gloves, biodynamics, transmissibility, impedance, hands, fingers

Practitioner summary

Increasing the contact force (i.e. push force or grip force) can increase or decrease the transmission of vibration through a glove. The vibration transmissibilities of gloves should be assessed with a range of contact forces to understand their likely influence on the exposure of the hand and fingers to vibration.

1. INTRODUCTION

A glove is required to pass a test before it can be considered an ‘anti-vibration glove’ (International Organisation for Standardization, 2013). In the test, subjects are required to hold a cylindrical handle and apply a push force of 50 N and a grip force of 30 N. When using vibratory tools, the push force and the grip force can be greater or less than specified in the standard. This is one of several factors that limits the value of a test in predicting the performance of a glove worn while operating powered tools (Griffin, 1998; Hewitt *et al.*, 2016; Welcome *et al.*, 2016).

Several studies have found that the transmissibility of a glove to the palm of the hand and to the fingers can be affected by the contact force (e.g., Laszlo and Griffin, 2011; Kuczyński, 2014; Dong *et al.*, 2004; Welcome *et al.*, 2014). With increasing contact force, it has been reported that the transmissibility of a glove may increase (Laszlo and Griffin, 2011) although this is not always the case (O’Boyle and Griffin, 2006). The force applied by a finger can greatly affect the mechanical impedance of a finger and the transmission of vibration to a finger (Mann and Griffin, 1996; Welcome *et al.*, 2014). The effects of force on glove transmissibility are expected to be complex, because the transmissibility depends on both the dynamic stiffness of the glove material and the dynamic response of the hand, and both of these can vary with the applied force. Previous research has not attempted to measure the relative importance of changes in the dynamic responses of gloves and changes in the dynamic response of the hand as the force varies.

The resonance frequency in the apparent mass of the hand increases with increasing force (Riedel, 1995; Burström, 1997; O’Boyle and Griffin, 2006; Marcotte *et al.*, 2005; Xu *et al*., 2011). The increase in the resonance frequency increases the apparent mass of the hand at frequencies greater than the resonance frequency. This increase in apparent mass can be expected to reduce glove transmissibility at frequencies greater than the resonance frequency, provided the dynamic stiffness of the material is unchanged by the increase in force (Rezali and Griffin, 2016a, 2016b).

In practice, increasing the force applied to a glove tends to increase the dynamic stiffness of the glove material (O’Boyle and Griffin 2006). The increase can be small or large depending on the material properties. In the extreme, the contact force can be sufficient to cause the material to ‘bottom out’, so that the transmissibility is close to unity at all frequencies of interest. The transmissibility of a glove tends to increase with increasing dynamic stiffness of the glove material (Rezali and Griffin 2014, 2016a, 2016b), so the transmissibility of a glove may be expected to increase when the force increases.

This paper is based on an experiment conducted in partial fulfilment of a PhD thesis (Rezali, 2015). The experiment investigated the effects of contact force on the dynamic response of the hand, the dynamic stiffness of glove materials, and the transmissibilities of the glove materials to the hand. The measurements were made at two different locations: the centre of the palm of the hand and the tip of the index finger. It was hypothesised that at frequencies greater than the principal resonance, the overall apparent mass at both locations (palm or index finger) would increase with increasing force. The dynamic stiffnesses of the glove materials were expected to increase at all frequencies as the force increased. Depending on the frequency of vibration, as the contact force increased, the transmissibilities of the glove materials to the hand were expected to increase or decrease in way that could be predicted from the measured changes in the apparent mass of the hand (or finger) and the dynamic stiffness of the material.

2. METHODS

2.1 Glove materials

The study was conducted with three samples of material, two foams and a gel (denoted as Foam A, Foam B, and Gel A), with thicknesses of 6.4, 6.0, and 5.0 mm, respectively. All samples were round with a diameter of 25 mm and a mass of less than 2 grams. Foam A and Gel A were cut from gloves that passed and failed, respectively, the test for an 'anti-vibration glove' in ISO 10819:1996. Both foams were closed-cell foams. All three samples weighed less than 2 grams. Foam A was perforated with 0.5-mm diameter holes. The samples were selected as representative of materials currently found in gloves.

2.2 Subjects

Ten subjects (8 males and 2 females) aged 24 to 42 years (median 29 years) participated in the experiment. Subject stature ranged from 160 to 181 cm (median 167 cm), weight 59 to 120 kg (median 67 kg), hand circumference 165 to 230 mm (median 200 cm), and hand length 172 to 205 mm (median 183 cm). The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (reference number 8824).

2.3 Measuring the apparent mass of the hand and the material transmissibility to the hand

Static force was measured using a force transducer (Kistler 4576A) attached to a steel plate secured on the table of a vibrator (Derritron VP30) orientated to provide vertical vibration. The dynamic force and the acceleration were measured using an impedance head (B&K 8001). Secured to the top of the impedance head was a 25-mm circular metal plate, weighing about 12 grams. Acceleration at the hand was measured using a miniature accelerometer installed in a 25-mm diameter wooden adapter, with a combined weight of 14 grams (Figure 1, left).

When measuring the apparent mass, subjects placed either their palm or the tip of their index finger on the circular wooden adapter and applied a downward push force of 10, 15, or 20 N. The arm was not otherwise supported. The same conditions were used when measuring material transmissibility, with the material placed between the metal plate and the wooden adapter. Subjects performed at least three practice trials before commencing the experimental measurements of apparent mass and transmissibility.

FIGURE 1 ABOUT HERE

A 10-s period of random vertical vibration (with an acceleration spectrum from 5 to 500 Hz) was generated using MATLAB (R2011b) with the *HVLab* toolbox (version 1.0). The vibration was presented at a magnitude of 2.0 ms^{-2} r.m.s. (frequency-weighted using W_h according to ISO 5349-1:2001; Figure 2).

The order of measuring either apparent mass or transmissibility, and the orders of presenting the three glove materials and the three forces were randomised.

FIGURE 2 ABOUT HERE

2.4 Measuring the material dynamic stiffness

Using equipment as shown in Figure 1 (right), the dynamic stiffnesses of the glove materials were measured with three preload forces: 10, 15, and 20 N. A 25-mm diameter sample of material was placed on a 25-mm diameter metal plate attached to the vibrator platform. In the upper part of the 'indenter rig', a force transducer was suspended through a bearing so that the required downward force could be applied to the material by turning the preload screw. An impedance head with a 25-mm metal plate was attached to the force transducer to measure the dynamic force during vibration. Vertical acceleration was measured using an accelerometer (B&K 4374) secured to the vibrator table.

A 10-s period of random vertical vibration (with an acceleration spectrum between 5 to 500 Hz as shown in Figure 2) was generated using MATLAB (R2011b) with the *HVLab* toolbox (version 1.0). The vibration was presented at a magnitude of 0.75 ms^{-2} r.m.s. (frequency-weighted). The vibration spectrum differed from that used to measure the apparent mass of the hand and the transmissibility of the material, due to the different dynamic conditions: the rigid indenter had impedance very different from that of the hand, so different acceleration was required to obtain easily measurable forces over the range 5 to 500 Hz.

2.5 Analysis

The data were acquired with a sampling rate of 4096 samples per second via low pass filters at 1000 Hz. Constant-bandwidth frequency analysis was performed across the frequency range 10 to 300 Hz with a frequency resolution of 2 Hz and 84 degrees of freedom.

Apparent mass

The masses supported on the force sensing elements of the impedance head influenced the measured force but their effect was eliminated by subtracting the vertical acceleration multiplied by the sum of these masses from the measured force in the time domain (Griffin, 1990).

The apparent mass of the hand, $M(f)$, was determined from the ratio of the cross-spectral density of the input acceleration and the output force, $F_{io}(f)$, to the power spectral density of the input acceleration, $A_{ii}(f)$ (Griffin, 1990):

$$M(f) = \frac{F_{io}(f)}{A_{ii}(f)} \tag{1}$$

The apparent mass of the hand with wooden adapter, $M_{hw}(f)$, was calculated using:

$$M_{hw}(f) = \frac{F_{hwio}(f)}{A_{ii}(f)} \tag{2}$$

where $F_{hwio}(f)$ is the force exerted at the wooden adapter and given by:

$$F_{hwio}(t) = F_{io}(t) - M_{s-w}(t)A_i(t) \tag{3}$$

where $M_{s\text{-}w}(t)$ is the mass of the equipment supported by the force cell of the impedance head excluding the wooden adapter.

Transmissibility

The transmissibility of the glove material, $T(f)$, was determined from the ratio of the cross-spectral density of the input and output acceleration, $a_{io}(f)$, to the power spectral density of the input acceleration, $a_{ii}(f)$ (Griffin, 1990):

$$T(f) = \frac{a_{io}(f)}{a_{ii}(f)} \tag{4}$$

Dynamic stiffness

The dynamic stiffness of glove material, $S(f)$ was given by:

$$S(f) = \frac{F_{Mio}(f)}{-\omega^{-2}A_{Mii}(f)} \tag{5}$$

where $F_{Mio}(f)$ is the cross-spectral density of the input acceleration and the output force transmitted by the material, $A_{Mii}(f)$ is the power spectral density of the input acceleration, and ω is the angular frequency ($\omega = 2\pi f$) (Griffin, 1990).

The dynamic stiffness of the material was assumed to be represented by $S(f) = k + ic\omega$, where k is the stiffness of the material and c is the material viscous damping coefficient.

2.6 Predicting the transmissibility of material to the palm and to the thenar eminence

A mechanical impedance model was used to predict the transmissibility of the material to the palm of the hand (Griffin, 1990; Rezali and Griffin, 2016a):

$$\frac{a_{io}(f)}{a_{ii}(f)} = \frac{\omega^{-2}S(f)}{\omega^{-2}S(f) - M_{hw}(f)} = T(f) \qquad (6)$$

3. RESULTS

The coherencies associated with all measures of dynamic stiffness, apparent mass, and transmissibility were greater than 0.8 at all frequencies in the range 10 to 300 Hz.

3.1 Dynamic stiffness and viscous damping of the glove material

The stiffness of all three materials (Foam A, Foam B, and Gel A) increased with increasing contact force (Figure 3). The damping of Foam A and Foam B was independent of contact force, whereas the damping of Gel A increased with increasing contact force.

FIGURE 3 ABOUT HERE

With the contact force increasing from 10 to 20 N, the increase in the stiffness of Gel A (47 to 75% depending on frequency) was greater than the increase in the stiffness of Foam A (32 to 55%) and Foam B (2 to 12%). With the 10-N contact force, Foam B had the greatest stiffness, but with 20-N contact force, Gel A had the greatest stiffness. With all three contact forces, Gel A had the greatest damping.

3.2 Apparent mass at the palm and at the index finger

The apparent masses showed variability among subjects (Figure 4) and differed between the palm and the tip of the index finger ($p<0.05$ at frequencies from 10 to 300 Hz for all contact force conditions; Wilcoxon).

FIGURE 4 ABOUT HERE

The first resonance frequency in the median apparent mass at the palm of the hand increased from 14, to 16 and 18 Hz as the force increased from 10, to 15 and 20 N, respectively (Figure 5; Friedman $p=0.0004$). At frequencies greater than about 56 Hz, the apparent mass at the palm increased with increasing contact force (Figure 5; Friedman $p<0.007$).

At frequencies less than 50 Hz, the ~~median~~ apparent mass at the tip of the index finger increased as the force increased (Figure 5; Friedman $p<0.05$). The apparent mass at the index finger was independent of contact force at frequencies greater than 70 Hz (Figure 5; Friedman $p>0.05$).

At all frequencies and with all three forces, the apparent mass was greater at the palm of the hand than at the tip of the index finger.

FIGURE 5 ABOUT HERE

3.3 Transmissibility of glove material to the palm and to the index finger

To the palm of the hand, with all three forces Foam A had a lower median transmissibility than Foam B and Gel A at frequencies greater than 60 Hz (Figure 6). The median transmissibilities of the three materials to the hand were less than 1.0 at all frequencies of vibration from 60 to 300 Hz. The transmissibility of Gel A was independent of contact force at all frequencies of vibration from 10 to 300 Hz (Friedman $p>0.05$ for Gel A) with the exception of frequencies between 56 and 76 Hz (Friedman $p<0.027$). Similarly, the transmissibility of Foam A was not significantly affected by the change in contact force at any frequency from 10 to 300 Hz (Friedman $p>0.05$), with exception of frequencies from 14 to 30 Hz, 50 to 74 Hz, and 138 to 170 Hz (Friedman $p<0.05$). However, at frequencies greater than 100 Hz the transmissibility of Foam B to the palm of the hand reduced as the contact force increased (Figure 6; Friedman $p<0.003$).

To the index finger, with all three forces Foam A had a greater transmissibility than Foam B and Gel A at all frequencies of vibration from 10 to 300 Hz (Figure 6). All three materials amplified the vibration to the finger at frequencies greater than about 100 Hz. For all three materials, the median transmissibilities were unaffected by force at frequencies less than 40 Hz (Friedman, $p>0.06$). The median transmissibilities of Gel A and Foam B were little affected by the contact force at any frequency (Figure 6; Friedman, $p>0.07$). The first principal resonance frequency in the transmissibility of Foam A increased with increasing contact force (Friedman, $p=0.006$), and with increased force the transmissibility reduced at frequencies less than the resonance and increased at frequencies greater than the resonance.

FIGURE 6 ABOUT HERE

Inter-subject variability in the transmissibilities to the palm and to the index finger are shown for each of the three materials in Figures 7, 8, and 9. For Foam A, transmissibilities were significantly greater to the fingers than to the palm for all frequencies greater than 20 Hz with a force of 10 N, greater than 54 Hz with a force of 15 N, and greater than 60 Hz with a force of 20 N (Wilcoxon $p<0.05$). For Foam B, transmissibilities to the finger were significantly greater than those to the palm at frequencies greater than 58 Hz, 62 Hz, and 70 Hz with 10, 15, and 20 N, respectively (Wilcoxon $p<0.05$). For Gel A, transmissibilities to the finger were significantly greater than those to the palm at frequencies greater than 56 Hz, 68 Hz, and 72 Hz with 10, 15, and 20 N, respectively (Wilcoxon $p<0.05$).

FIGURES 7, 8 and 9 ABOUT HERE

3.4 Predicted transmissibility of the glove material to the palm and to the index finger

The measured and predicted transmissibilities of Foam A, Foam B, and Gel A are compared for individual subjects (in Figures 7, 8, and 9) and for the median transmissibility (in Figure 10). The predicted transmissibilities were calculated from the measured dynamic stiffness of the material and the apparent mass measured at the palm of the hand or the tip of the index finger.

To the palm of the hand, with all three contact forces the predicted transmissibilities of Foam A are similar to the measured transmissibilities at frequencies less than 150 Hz (Friedman, $p>0.058$) but underestimate the measured transmissibility at frequencies greater than 150 Hz (Friedman, $p<0.048$; Figure 10). The predicted transmissibilities of Foam B to the palm of the hand are similar to the measured transmissibility at all frequencies, although small differences at frequencies greater than 120 Hz are statistically significant (Friedman, $p<0.041$). The predicted transmissibilities of Gel A to the palm of the hand are similar to the measured transmissibility at all frequencies from 10 to 300 Hz (Friedman, $p>0.05$).

To the index finger, with all three contact forces the predicted transmissibilities slightly underestimated the measured transmissibilities at frequencies greater than 70 Hz for Foam A (Friedman, $p<0.033$) and at frequencies greater than 40 Hz for Gel A (Friedman, $p<0.043$). For Foam B, the predicted transmissibility to the index finger are similar to the measured transmissibilities at all frequencies from 10 to 300 Hz (Friedman, $p>0.05$), with exception of frequencies between 80 to 130 Hz (Friedman, $p<0.039$).

FIGURE 10 HERE

4. DISCUSSION

4.1 Dynamic stiffness of the glove materials

As the contact force increased, Foam A and Gel A showed much greater percentage increases in dynamic stiffness than Foam B. Gel A showed a greater absolute increase in stiffness and damping than the other two materials. Foam B had the greatest stiffness with 10 N contact force but as the contact force increased, the material that had the greatest stiffness changed to Gel A. Such changes in the dynamic stiffness of a glove show that contact force could affect the transmissibility of a glove. However, the transmissibility of a glove also depends on the apparent mass of the hand or finger, which also changes with changes in contact force (see below).

Foam A was perforated by 0.5-mm diameter holes at 2-mm intervals, which may have reduced the contact area. Reducing the area of contact of a solid material reduces the stiffness and damping of the material (Rezali and Griffin, 2016). Perforations reduce the contact area but the contact area becomes dependent on the applied force because the perforations close as the force increases. So the dynamic performance of a perforated material can be expected to be highly dependent on the applied force, although there are no known studies.

4.2 Apparent mass at the palm and at the finger

At the palm of the hand, the apparent mass increased with increasing force at frequencies greater than about 56 Hz. This is consistent with previous findings (O'Boyle and Griffin, 2006; Xu *et al*., 2011) that also show changes at lower frequencies, possibly due to the use of a wider range of push forces than employed in the present study. Increased force can be expected to increase the stiffness of the arm and the hand and increase the resonance frequency in the apparent mass, with associated increases in the apparent mass at frequencies higher than the resonance frequency (Figure 5).

At the tip of the index finger, there was also an increase in the apparent mass with increasing contact force at frequencies greater than the resonance, although the effect of contact force on the apparent mass at the index finger was less than at the palm and not statistically significant at frequencies greater than 70 Hz.

The increases in the apparent mass of the hand and finger with increasing contact force mean that grip force and push force can affect the transmissibility of a glove irrespective of whether the force affects dynamic stiffness of the glove material.

The apparent mass measured at the palm and at the index finger is compared with the apparent mass measured in previous studies in Figure 11. The apparent masses at the palm and at the index finger measured in this study are similar to the apparent masses measured in previous studies that have similar contact conditions (i.e., similar contact force, contact area, and posture; Rezali and Griffin, 2014) but different subjects.

The apparent mass at the palm of the hand in this study was measured on flat surface with vertical vibration. Vibration was not directed into the forearm and body of subjects as in the test for 'anti-vibration gloves' in International Standard ISO 10819. A frequency-dependent difference can be expected between the apparent mass measured in this study and the apparent mass measured in a posture similar to the standard (see Dong *et al.*, 2012). At all frequencies of vibration, the apparent mass measured at the palm of the hand with 20-N contact force in this study (where the vibration was not directed into the forearm and body of subjects but was in x_h-axis of the hand using the coordinate system in ISO 5349-1) is less than the apparent mass measured at the palm with 50-N contact force on a cylindrical handle (where vibration was directed into the forearm and body of subjects in the z_h-axis using the coordinate system of the hand in ISO 5349-1; Figure 11; Dong *et al.*, 2005).

FIGURE 11 ABOUT HERE

4.3 Effect of contact force on the transmissibility of the glove materials to the palm and to the fingers

Similar to a previous study (O'Boyle and Griffin, 2006), increasing the contact force had little effect on the transmissibility of Foam A or Gel A to the palm of the hand. It seems that as the contact force increased, the combined increase in the apparent mass at the palm and the increase in the dynamic stiffness (of Foam A and Gel A) resulted in little or no effect on glove transmissibility. However, the stiffness and damping of Foam B were not significantly affected by the contact force and so the increase in the apparent mass with increasing force reduced the transmissibility to the palm of the hand (Figure 6).

Contact force seems to have little effect on the apparent mass of the index finger. So an increase in the dynamic stiffness of glove materials with increasing force will tend to increase the resonance frequency in material transmissibility and increase transmissibility to the index finger at frequencies greater than the resonance. This was observed for Foam A. For Gel A and Foam B, the resonance in the transmissibility to the index finger occurred at frequencies greater than 300 Hz and so the effect of contact force on the resonance frequency with either material could not be identified.

4.4 Predicting the effects of contact force on glove transmissibility

Both the apparent mass of the hand and the dynamic stiffness of the glove materials were affected by an increase in the contact force. The transmissibilities of each of the three materials reflected the combined effect of changes in the dynamic stiffness of the material and changes in the dynamic response of the hand, but in different ways (see Section 4.3).

To better understand the importance of combined increases in the apparent mass and the dynamic stiffness on transmissibility as the contact force increases, the transmissibility of Foam A to the palm of the hand was predicted for three cases: 1. The dynamic stiffness varying with contact force but the apparent mass fixed at that measured with a contact force of 10 N; 2. The apparent mass varying with contact force but the dynamic stiffness fixed at that measured with a contact force of 10 N; 3. Both apparent mass and dynamic stiffness varying with contact force, as in this study.

For Case 1, the predicted transmissibility to the palm of the hand reduced at high frequencies as the contact force increased (Figure 12). This is similar to the effect of contact force on the transmissibility of Foam B to the palm of the hand as measured in this study (Figure 6).

FIGURE 12 ABOUT HERE

For Case 2, the predicted transmissibility to the palm of the hand at frequencies greater than the first resonance increased with increasing contact force. This trend is similar to the trend reported with various gloves (Laszlo and Griffin, 2011).

For Case 3 (i.e., predicted transmissibility as in this study and as shown in Figure 7), as the contact force increases the predicted transmissibility to the palm of the hand is unchanged at high frequencies. It may be concluded that the combined increase in the apparent mass and the increase in the material dynamic stiffness have resulted in little or no effect of contact force on transmissibility, as discussed in Section 4.3.

4.5 Implications for the testing of gloves

Both the dynamic properties of the hand and the dynamic properties of a glove can be affected by force, and it is these two characteristics that determine the vibration transmissibility of a glove.

The extent of the effect of force will depend on the properties of the glove material and the range of forces applied. The effects are potentially much greater than found in this study, which was restricted to only three materials and a 2:1 range of forces.

The study shows that the effects of force on transmissibility to both the palm of the hand and the finger can be usefully predicted from the dynamic stiffness of the material and the apparent mass of the hand. This approach makes it possible to optimise the dynamic performance of a material over a range of forces.

Although this study refers to force, the pressure will often be the factor influencing the dynamic performance of materials. In this study, the force was in the range 10 to 20 N and applied over an area of about 5 cm^2, giving pressures in the range 2 to 4 N/cm^2. The test defined in ISO 10813:2013 uses a 40-mm diameter cylindrical handle with a grip force of 30 N and a feed force of 50 N, which will give pressures that vary over the surface of a glove in contact with the handle and differ between gloves. The handles of powered tools are usually not simple cylinders and so a different distribution of pressures will occur. So, even if all tools required the same grip force and the same push force as defined for the standardised test, the vibration transmissibility of a glove measured according to ISO 10819:2013 will not be the same as that when the glove is used with vibratory tools.

This study should not be assumed to show that gloves provide any useful attenuation of the vibration experienced on powered tools. The measurements and predictions in this study and in recent previous studies (Rezali and Griffin, 2016a; Hamouda *et al.*, 2018), show that gloves can appreciably increase the vibration of the fingers compared to the palm, where vibration-induced vascular and neurological disorders are common. There may be some attenuation of the vibration transmitted to the palm of the hand at some frequencies, but a glove will only be effective if it attenuates those frequencies of vibration that are present on tools and cause damage in the hand (see Griffin, 1998).

It would be prudent for the effect of contact force (or pressure) to be included in the assessment of the vibration performance of gloves. The range of forces should encompass the range of pressure distributions that commonly occur when gloved hands grip the handles of powered tools. Otherwise, a glove can be optimised to pass a test by compromising its performance when used with a wider range of forces and pressure distributions that occur in work with powered vibratory tools.

5. CONCLUSIONS

Increasing the contact force increases the apparent mass of the hand at frequencies greater than the principal resonance, due to increased coupling of the arm, the hand, and the fingers with the vibration driving point. The apparent mass of the fingers increases with increased contact force at low frequencies, but with less effect of contact force at higher frequencies.

Increasing the contact force also tends to increase the stiffness and damping of glove materials, although increases are likely to be non-linear and will depend on material properties.

As the contact force increases, the resonance frequency in the transmissibility of a material to the hand can either increase (due to an increase in material dynamic stiffness) or decrease (due to an increase in the apparent mass of the hand). An increase in contact force can therefore either raise or lower the transmissibility at frequencies greater than the principal resonance.

In this study, transmissibilities to the palm of the hand with Foam A and Gel A were little affected by increases in contact force. The transmissibility of Foam B to the palm of the hand reduced as the contact force increased. For all three materials, as the contact force increased, the transmissibility to the index finger was not greatly affected at low frequencies.

The measured and predicted performance of a glove in attenuating vibration varies depending on the force applied to the glove. A wide range of applied contact forces is therefore suggested when assessing the dynamic performance of gloves in transmitting vibration to the hand and fingers.

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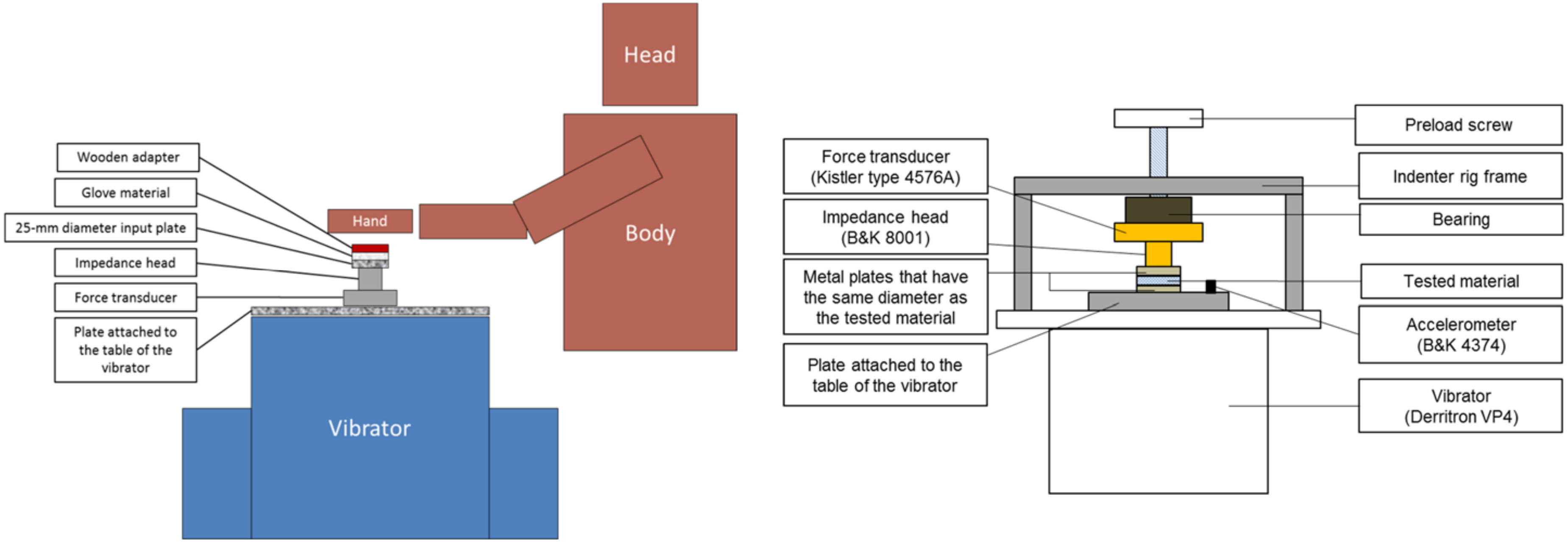

Figure 1 Posture of the hand for the measurement of the apparent mass at the palm of the hand (left) and diagrammatic representation of the rig used to determine the dynamic stiffness of the material.

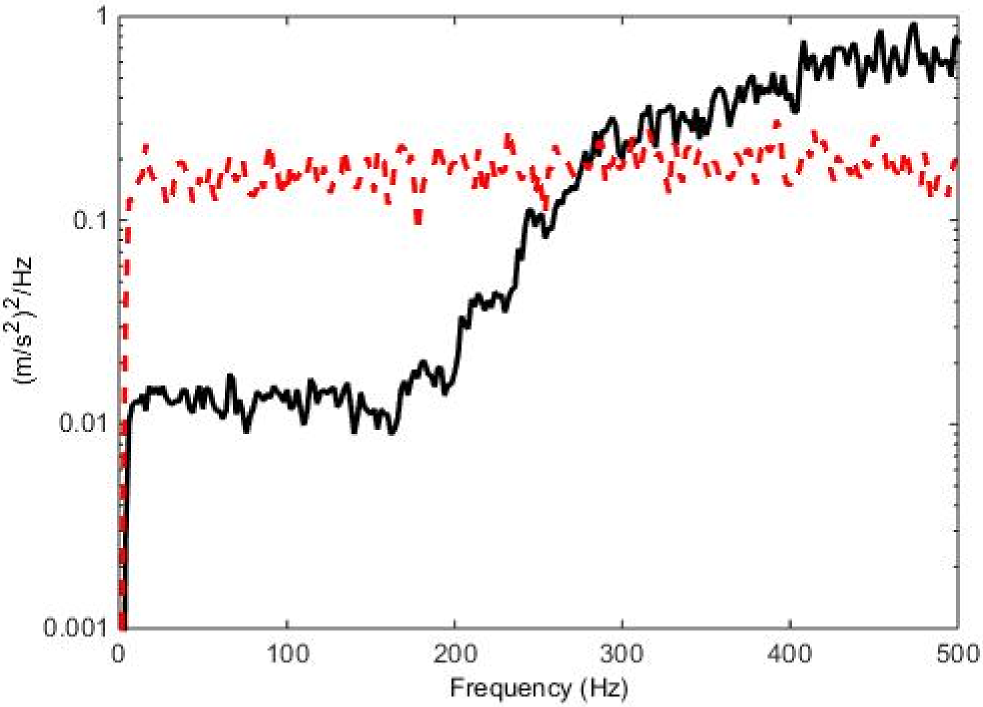

Figure 2 Acceleration power spectral densities of the stimuli: ––– for the measurement of apparent mass and transmissibility, ▬▬ for the measurement of dynamic stiffness. Spectra with 10-Hz resolution.

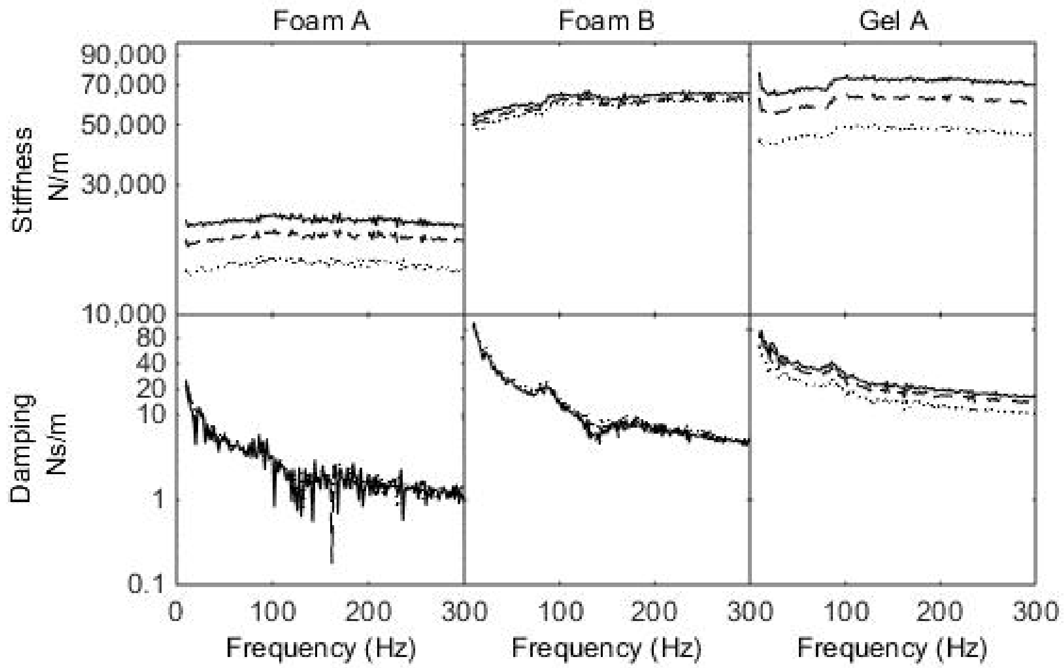

Figure 3 Stiffness and damping of the three materials as a function of the contact force in logarithmic scale (······· 10 N, ---- 15 N, ——— 20 N,).

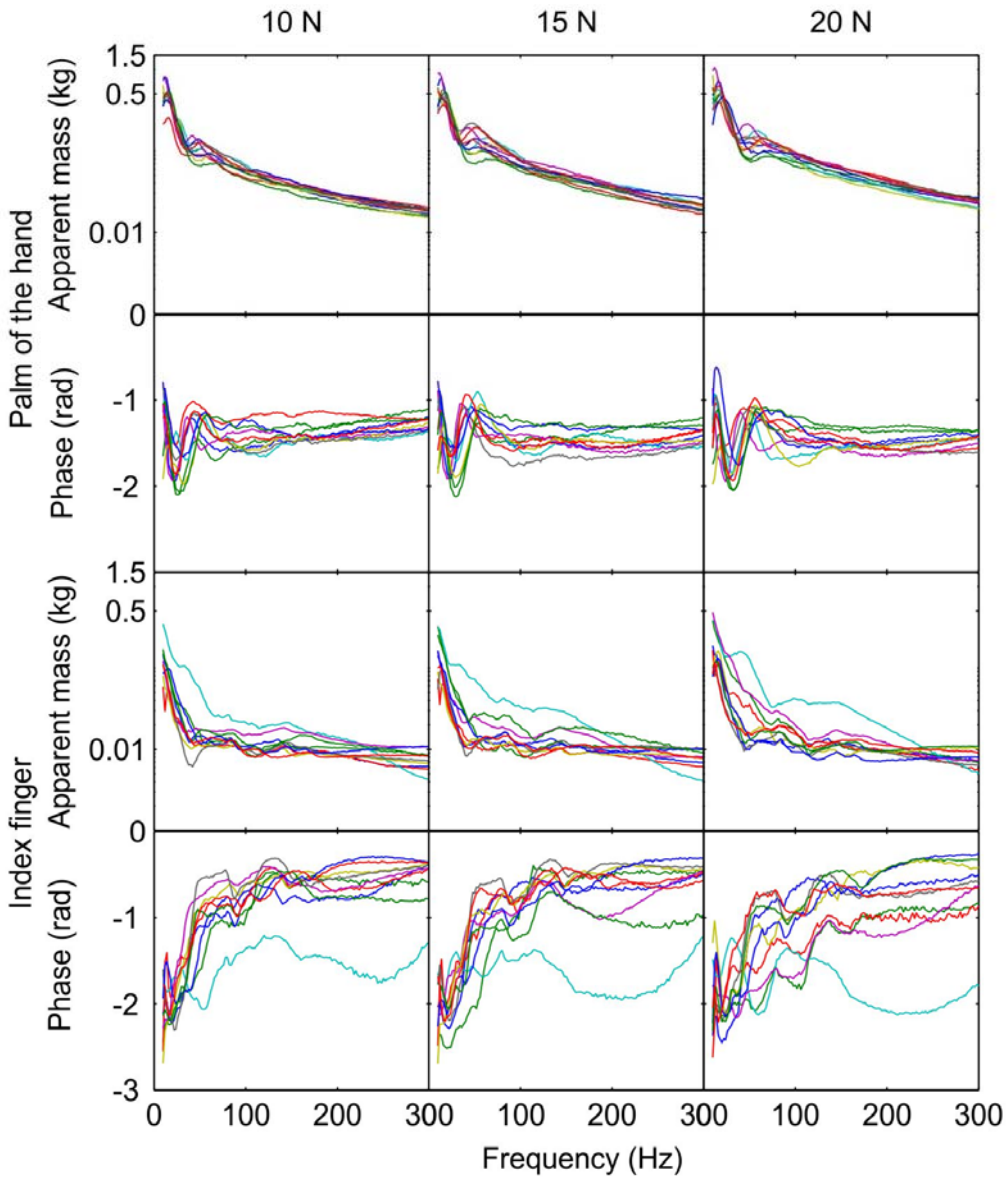

Figure 4 Apparent mass (modulus and phase; modulus in logarithmic scale) at the palm of the hand and at the tip of the index finger as a function of frequency and contact force. (Individual data for 10 subjects).

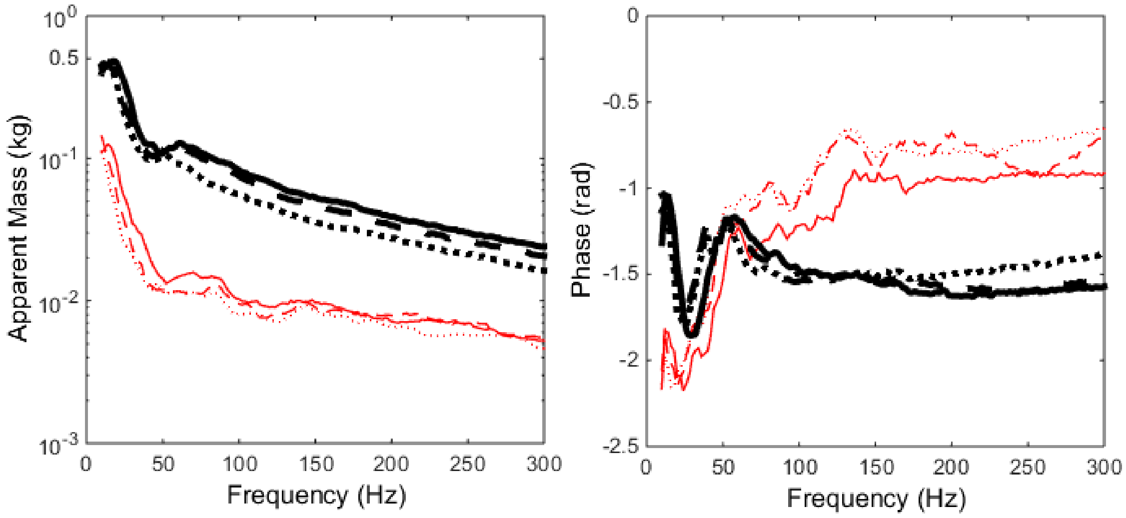

Figure 5 Apparent mass at the palm and at the index finger with contact force of 10, 15, and 20 N (thicker lines in black - Palm; thinner lines in red - Index finger; ······· 10 N, ---- 15 N, ——— 20 N). Median values from 10 subjects.

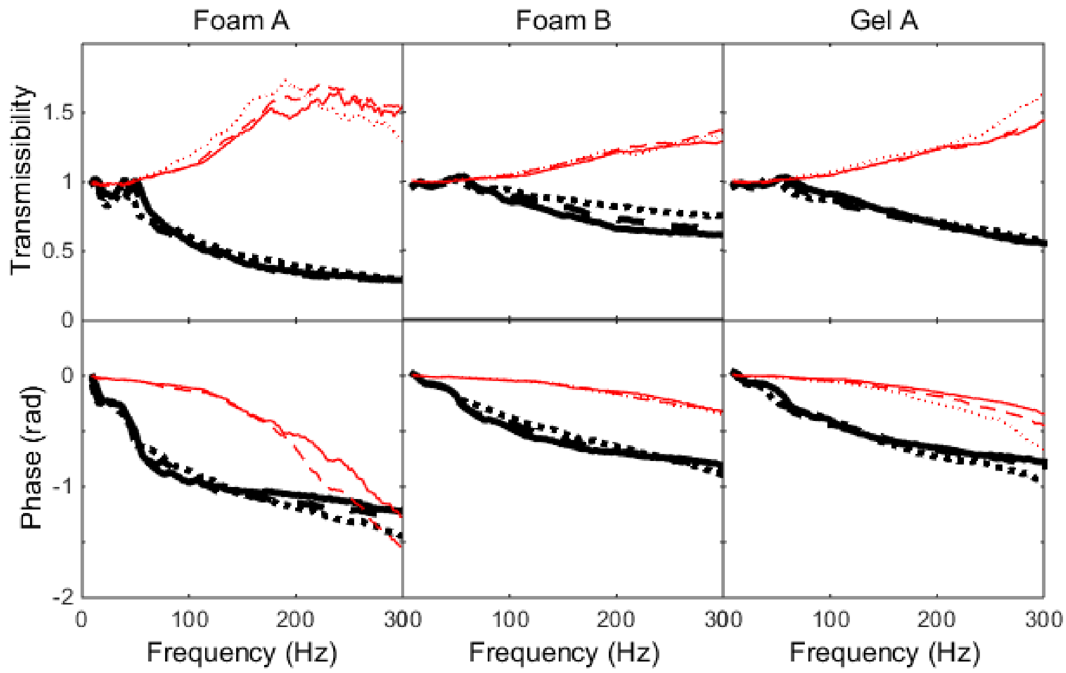

Figure 6 Transmissibilities of all materials to the palm and to the index finger (thicker lines in black - Palm; thinner lines in red - Index finger; ······· 10 N, ---- 15 N, ——— 20 N). Median values from 10 subjects.

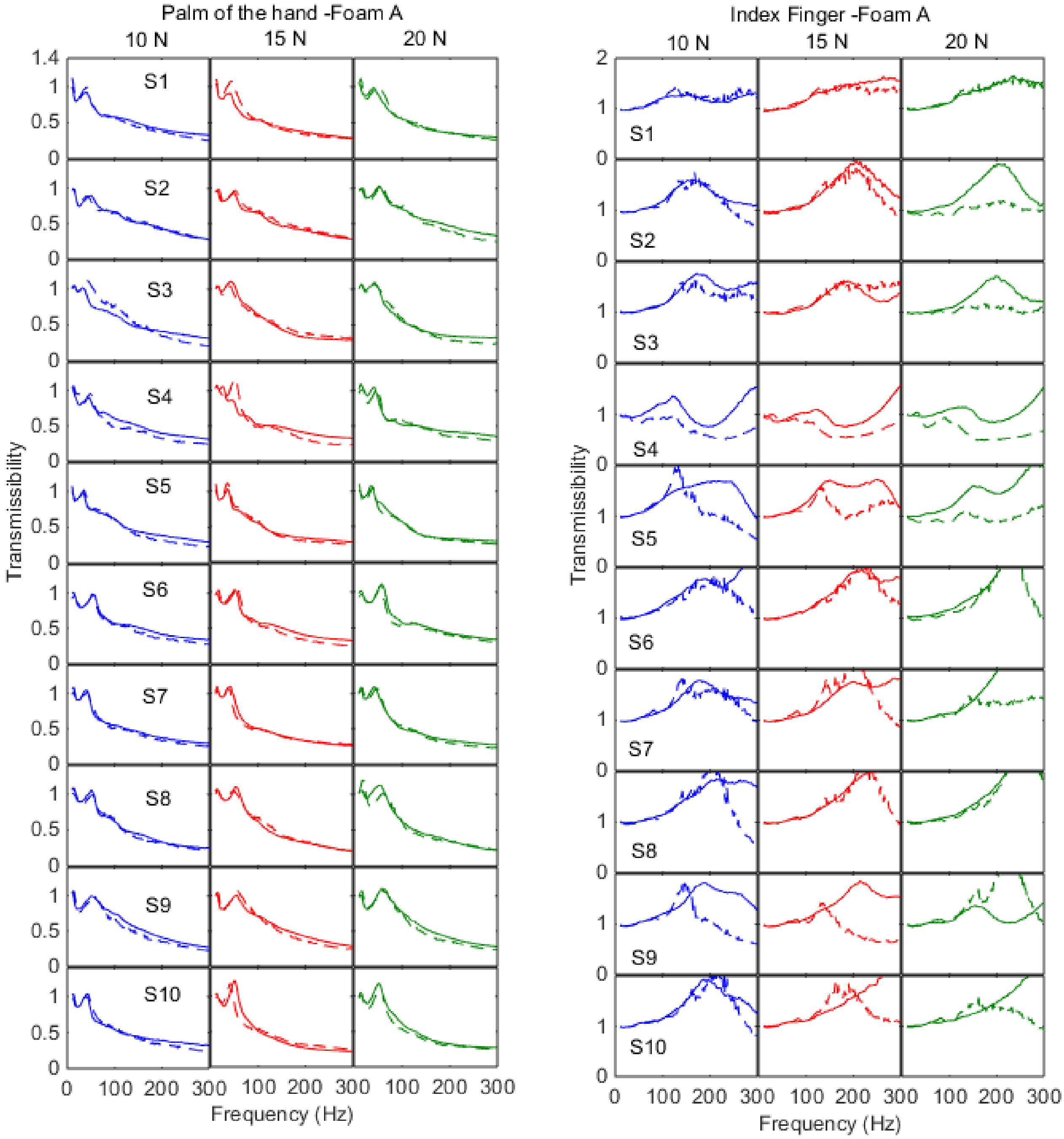

Figure 7 Individual transmissibilities from 10 subjects (measured and predicted) of Foam A to the palm and to the index finger according to contact force: ——— 10 N, ——— 15 N, ——— 20 N; continuous lines - measured; broken lines - predicted.

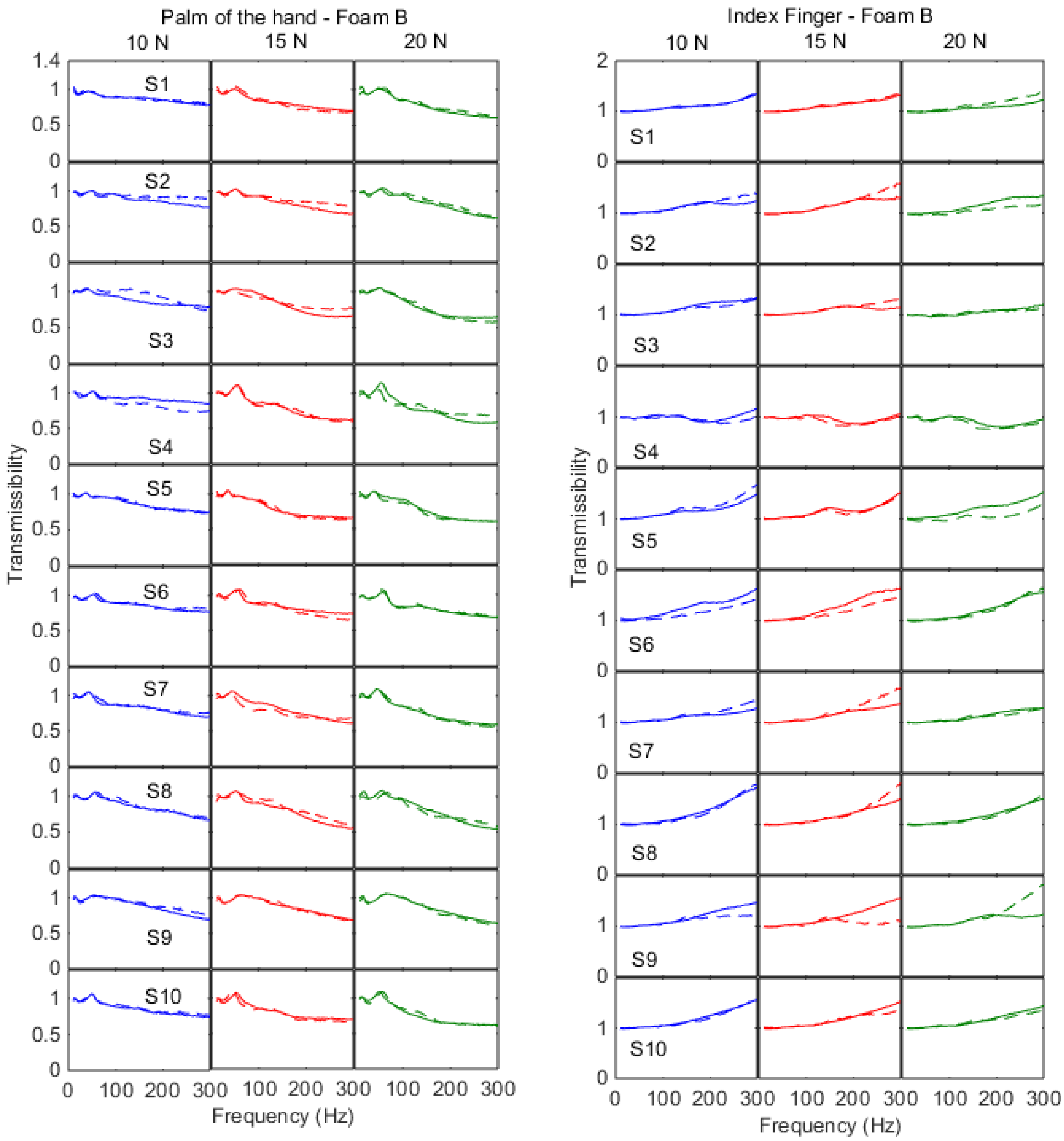

Figure 8 Individual transmissibilities from 10 subjects (measured and predicted) of Foam B to the palm and the index finger according to contact force: 10 N, 15 N, 20 N; continuous lines - measured; broken lines - predicted.

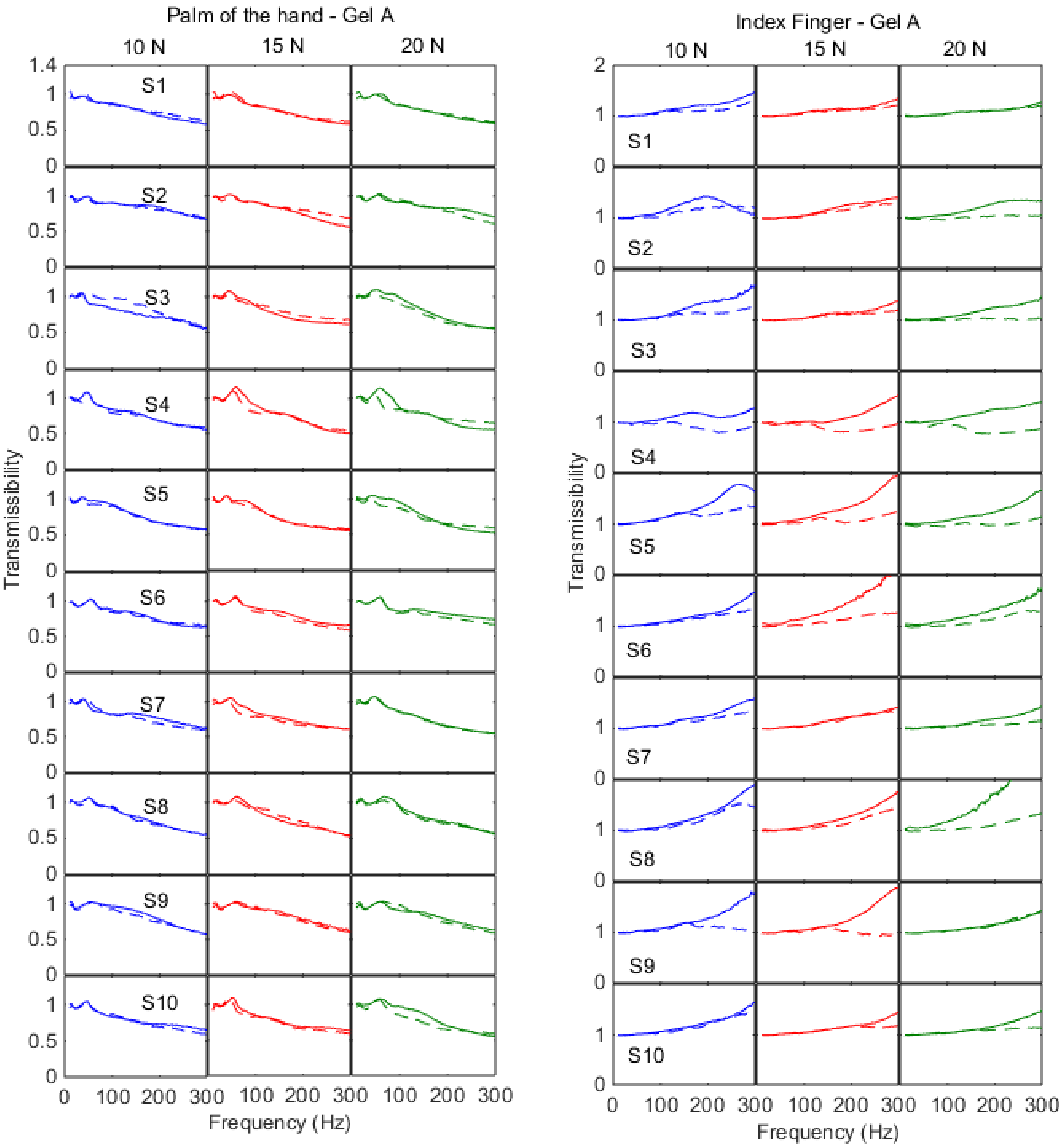

Figure 9 Individual transmissibilities from 10 subjects (measured and predicted) of Gel A to the palm and the index finger according to contact force: ——— 10 N, ——— 15 N, ——— 20 N; continuous lines - measured; broken lines - predicted.

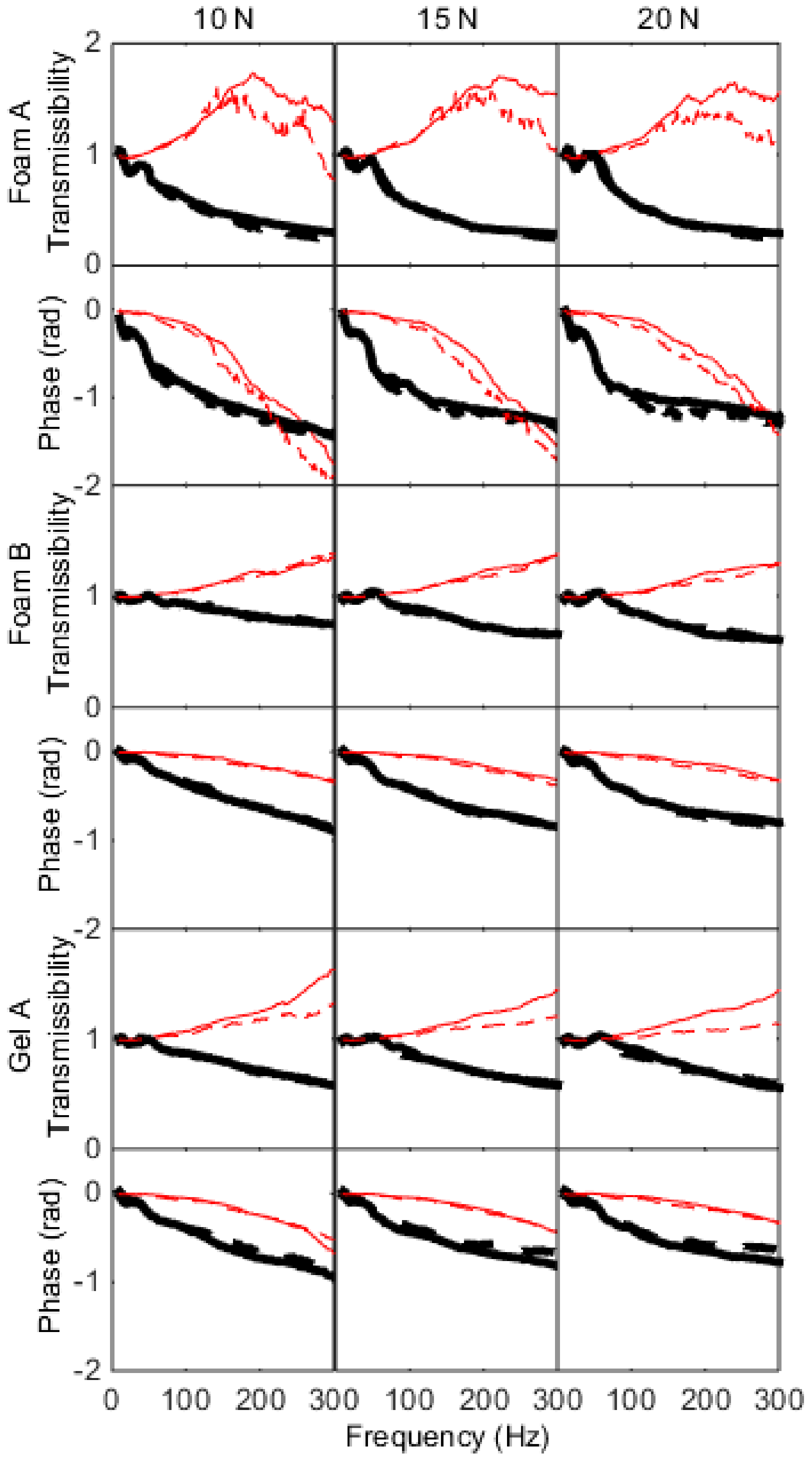

Figure 10 Transmissibility (measured and predicted) for Foam A, Foam B, and Gel A to the palm and to the index finger according to contact force: thicker lines - Palm, thinner lines - Index finger; continuous lines - measured, broken lines – predicted. Median values from 10 subjects.

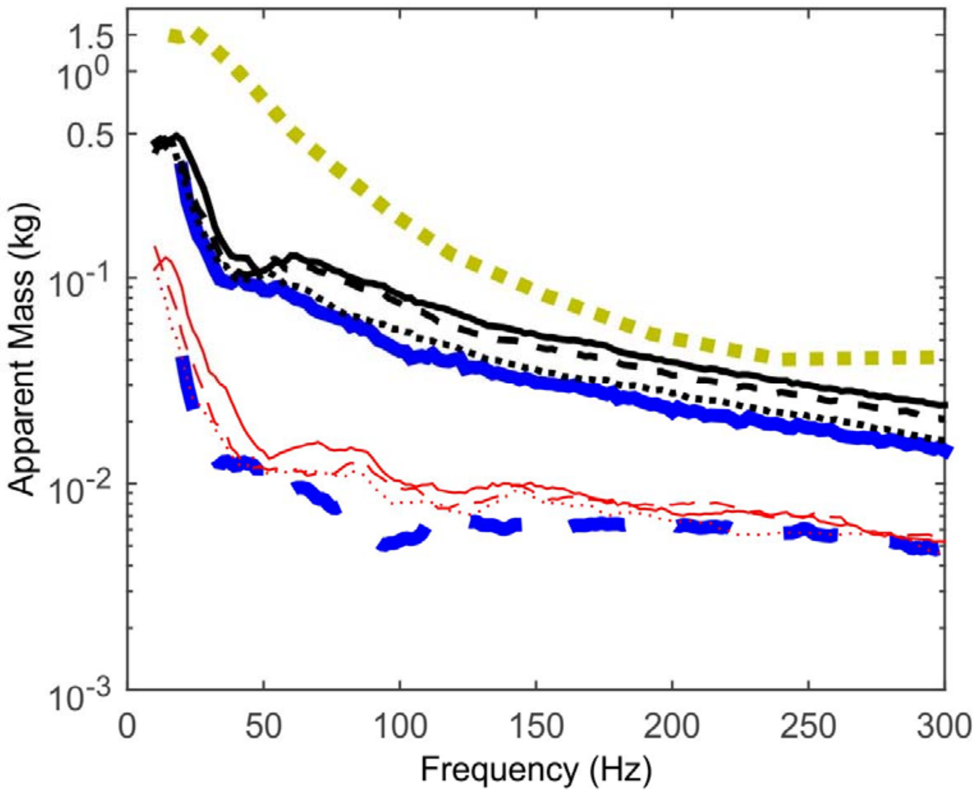

Figure 11 Median measured apparent mass at the palm of the hand, vertical direction, this study (——— 20 N, – – – – 15 N, ······· 10 N); median measured apparent mass at the index finger, x_h-axis based on coordinate system in ISO 5349-1, this study (——— 20 N, – – – – 15 N, ······· 10 N); Palm pushing a flat surface at 10 N on a 25-mm diameter plate, x_h-axis based on coordinate system in ISO 5349-1, Rezali and Griffin (2014), (———); Index Finger pushing a flat surface at 10 N on a 25-mm diameter plate, x_h-axis based on coordinate system in ISO 5349-1, Rezali and Griffin (2014), (▬ ▬ ▬ ▬); and Palm pushing a cylindrical handle with adapter at 50 N, z_h-axis based on coordinate system in ISO 5349-1, Dong et al. (2005), (■■■ ■■).

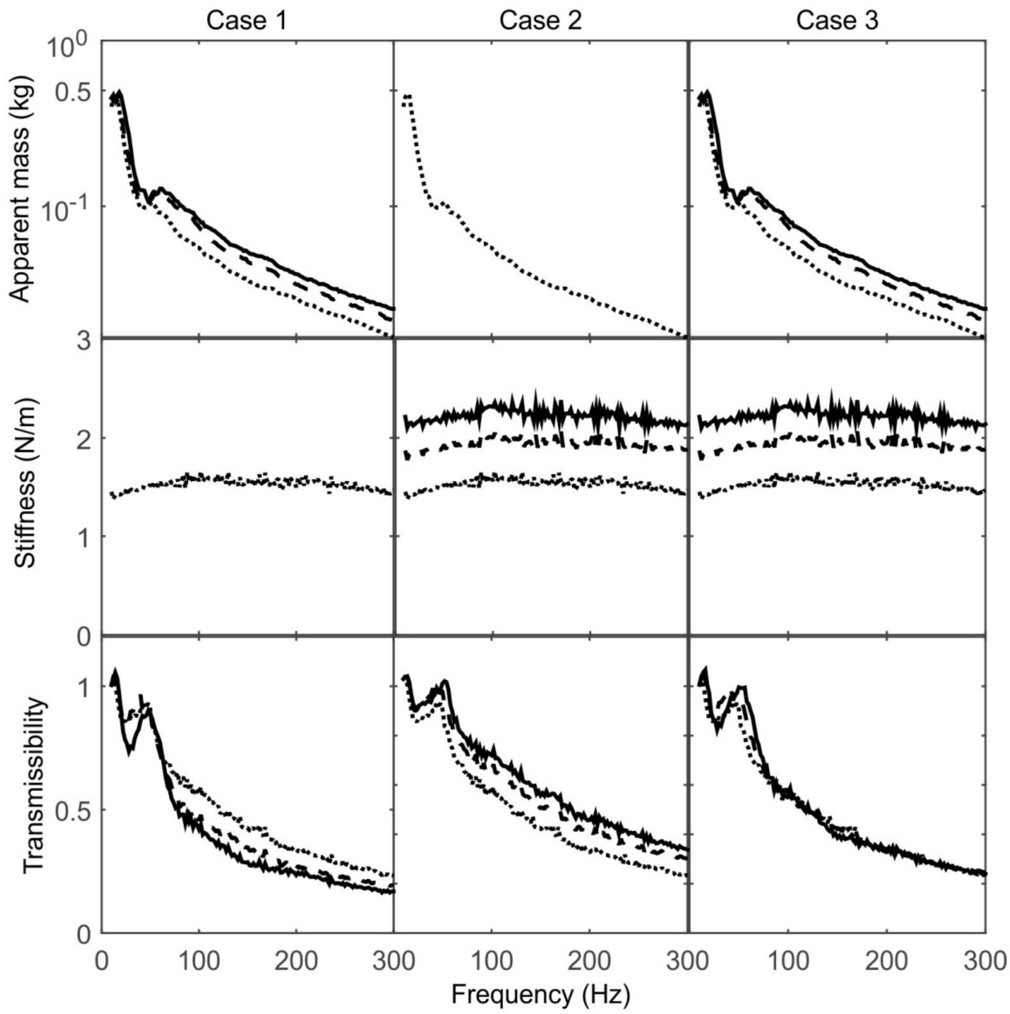

Figure 12 The predicted transmissibility (modulus) of Foam A to the palm of the hand for three cases: (Case 1) the dynamic stiffness unaffected by the contact force, (Case 2) the apparent mass unaffected by the contact force, (Case 3) both apparent mass and dynamic stiffness affected by the area of contact area, as in this study, according to the contact force conditions (····· 10 N, −−−− 15 N, ——— 20 N). Median values from 10 subjects.